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The 3D soft X-ray cluster-AGN cross-correlation function in the *ROSAT* NEP survey

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Abstract.   X-ray surveys facilitate investigations of the environment of AGNs. Deep *C*handra observations revealed that the AGNs source surface density rises near clusters of galaxies. The natural extension of these works is the measurement of spatial clustering of AGNs around clusters and the investigation of relative biasing between active galactic nuclei and galaxies near clusters.The major aims of this work are to obtain a measurement of the correlation length of AGNs around clusters and a measure of the averaged clustering properties of a complete sample of AGNs in dense environments. We present the first measurement of the soft X-ray cluster-AGN cross-correlation function in redshift space using the data of the *ROSAT*-NEP survey. The survey covers 9×9 deg^2 around the North Ecliptic Pole where 442 X-ray sources were detected and almost completely spectroscopically identified. We detected a $>3\sigma$ significant clustering signal on scales $s \leq 50\ h_{70}^{-1}$ Mpc. We performed a classical maximum-likelihood power-law fit to the data and obtained a correlation length $s_0 = 8.7_{-0.3}^{+1.2}\ h_{70}^{-1}$ Mpc and a slope $\gamma = 1.7_{-0.7}^{+0.2}$ (1σ errors). This is a strong evidence that AGNs are good tracers of the large scale structure of the Universe. Our data were compared to the results obtained by cross-correlating X-ray clusters and galaxies. We observe, with a large uncertainty, that the bias factor of AGN is similar to that of galaxies.

1. Introduction

In the present paper, we concentrate on the study of the relative clustering between X-ray selected AGNs and galaxy clusters. Our work improves on most previous work on the large-scale structure of X-ray selected AGNs in two important aspects. First, with the exception of Mullis et al. (2004), our sample is the only one that is spectroscopically complete (99.6%). Gilli et al. (2005) used the CDFS (35%) and the CDFN (50%). The Basilakos et al. (2005) sample had almost no spectroscopic redshifts. Yang et al. (2006) used the CLASXS sample (52% complete) and the CDFN (56% complete). Second, with the exception

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of Mullis et al. (2004) and part of Yang et al. (2006), we measure a three dimensional redshift space correlation function as opposed to deprojecting the two dimensional angular correlation function.

Another motivation for our work is that over the last several years, X-ray observations revealed that a significant fraction of high-z clusters of galaxies show overdensities of AGNs in their outskirts (i.e. between 3 h_{70}^{-1} Mpc and 7 h_{70}^{-1} Mpc from the center of the cluster) (Henry et al., 1991; Cappi et al., 2001; Ruderman & Ebeling 2005, Cappelluti et al., 2005, and references therein). These overdensities were however detected in randomly selected archive targeted observations of galaxy clusters. While these overdensities are highly significant (up to 8σ) when compared to cluster-free fields, the incompleteness of the samples does not allow drawing any conclusion about the average clustering properties of AGNs around clusters. The majority of the sources making these overdensities have no spectroscopical identification and therefore any information on their spatial clustering is lost. More recently Branchesi et al. (2007) showed that at high-z the source surface density of AGNs significantly increases even in the central regions of the clusters. These results imply that further progress will come from studying the three dimensional spatial distribution of AGNs around clusters. A natural way to characterize this specific type of clustering is given by the three-dimensional *cross*-correlation of AGNs and galaxy clusters, the computation of which needs complete redshift information for all objects, which is rare in X-ray surveys.

2.   The Cluster AGN cross-correlation function

The cross-correlation function ξ_{CA} of clusters and AGNs is defined by the joint probability to find, at a distance r, one cluster in the infinitesimal comoving volume element δV_C and one AGN in the comoving volume element δV_A, $\delta P = n_C n_A [1 + \xi_{CA}(r)] \delta V_C \delta V_A$, where n_C and n_A are the mean comoving number densities of clusters and AGNs, respectively. In calculating the differential cross-correlation in redshift space we used an adapted version of the Landy–Szalay estimator (Landy & Szalay, 1993; see also e.g. Blake et al., 2006).

We present the spatial cross-correlation function between clusters and AGNs in left panel of Fig. 1. A positive clustering signal is detected in the distance interval $s \leq 50$ h_{70}^{-1} Mpc. In order to test the strength of the clustering we performed a canonical power-law fit, $\xi_{CA}(s) = (\frac{s}{s_0})^{-\gamma}$, with s_0 and γ as free parameters. The best fit parameters obtained are $s_0 = 8.7^{+1.2}_{-0.3}$ h_{70}^{-1} Mpc and $\gamma = 1.7^{+0.2}_{-0.7}$ where the uncertainty is at the 1σ confidence level. With γ fixed to 1.8 (i.e. a typical value found in galaxy-galaxy correlation function) we find $s_0 \sim 8.5 h_{70}^{-1}$ Mpc. A similar value was obtained by extending the fitting region to 60 h_{70}^{-1} Mpc and restricting it to the 2.5–40 h_{70}^{-1} Mpc.

3.   Discussion

We presented here the first direct evidence of spatial clustering of soft X-ray selected AGNs around X-ray selected clusters of galaxies. Indirect evidence was presented by Henry et al. (1991), Cappi et al. (2001), Cappelluti et al. (2005)
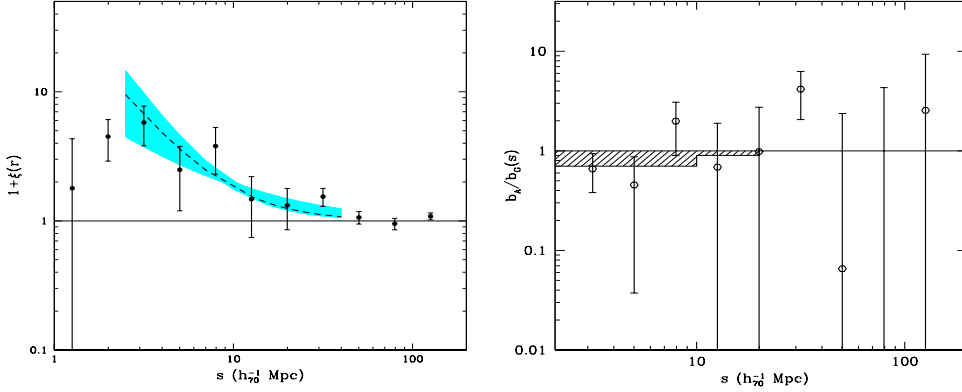
Figure 1.   *Left Panel* : The Cluster-AGN soft X-ray cross correlation function plus one. The error bars are quoted at 1σ level. The dashed line represents the best fit maximum-likelihood power-law fit $s_0=8.7^{+1.2}_{-0.3}$ h^{-1}_{70} Mpc and $\gamma=1.7^{+0.2}_{-0.7}$. The shaded region illustrates the 1σ confidence region of the power-law fit in the distance range in which it was performed. *Right Panel*: The ratio between the observed *ROSAT* NEP $\xi_{CA}(s)$ and the best fit $\xi_{CG}(r)$ obtained by Sánchez et al. (2005). Errors are quoted at the 1σ level. The shaded region shows the expected level of $\frac{b_A}{b_G}(s)=1$ if the cross-correlation functions were compared in the same space.

(and references therein). These authors found significant X-ray point source overdensities (about a factor 2) around distant clusters of galaxies when compared to cluster-free fields. If the overdensities were at the cluster redshift they would arise at scales smaller than ~ 7 h^{-1}_{70} Mpc. Since the correlation function is proportional to $(\frac{\delta\rho}{\rho})^2$, a $\xi_{CA}=1$ implies an overdensity of a factor 2 with respect to a randomly distributed field. We can conclude that, since the correlation length found in this work reflects the scale of the overdensities known up to now, we observe a physical overdensity (of at least a factor 2) of AGNs around clusters between 2 and ~ 8 h^{-1}_{70} Mpc from the center of the clusters.

Because of the shallowness of the NEP survey, the AGN surface density (i.e. <30 deg^{-2} in the central region) does not allow detection of such a correlation via overdensity analysis since it would be dominated by small number statistics. In fact, from our results we expect to detect AGNs overdensities on scales <7-8 h^{-1}_{70} Mpc from the center of clusters. At $<z>\sim 0.18$ (i.e. the median z of the cluster sample of the NEP survey) these overdensities arise on scales of ~ 0.6 deg^{-2} which are easily resolved by the NEP survey. However to significantly detect these overdensity on single clusters, a conspicuous number of sources is necessary to disentangle real overdensities from shot noise. As a final check we compared our ξ_{CA} to the X-ray cluster-galaxy cross-correlation function (hereinafter CGCCF) computed by Sánchez et al. (2005). They used the X-ray selected clusters of the REFLEX survey (Böhringer et al. 2002) and the galaxies from the APM survey (Maddox et al. 1990) limited to b$_j$=20.5 mag. They found that the CGCCF behaves like a broken power-law with a cut-off distance of ~ 2 h^{-1}_{70} Mpc with a steeper slope at small distances. We can define

the following approximate biasing relations:

$$\xi_{CA}(s) = b_C b_A \xi_\rho(s), \quad \xi_{CG}(s) = b_C b_G \xi_\rho(s). \tag{1}$$

Here $\xi_\rho(s)$ is the autocorrelation of matter, b_G, b_A and b_C are the bias factors relative to galaxies, AGNs and clusters, respectively. By dividing the two equations we can then derive $\frac{b_A}{b_G}(s)$. In order to perform this operation several effects must be taken in account. The ratio $\frac{b_A}{b_G}(s)$ is plotted in right panel of Fig. 1 as a function of the distance from the center of the cluster. The shaded region shows the value of our measurement that implies that $\frac{b_A}{b_G}(s)=1$ when taking into account the difference between real and redshift space measurements discussed in the previous paragraph. The ratio is consistent with 1 on almost all scales. We cannot exclude, within the errors, much different values of the relative bias. Our data suggest an average relative bias consistent with unity but allow an upper limit of ~6 (at 1σ) at separations $s < 50\ h_{70}^{-1}$ Mpc. For separations $s > 10$ h_{70}^{-1} Mpc no lower limits bigger than zero can be given. On larger scales the error increase thus it is difficult to draw any conclusion. At large separations the power-law shape of ξ_{CG} becomes uncertain, this makes a comparison of our data with those of Sánchez et al. (2005) less meaningful. We cannot exclude a significant antibiasing of AGNs when compared to galaxies, especially at low separations. Though the amplitude of the uncertainties of our data still allows a fluctuation in the relative biasing of more than a factor 2, we can conclude with a precision of 1σ that the probability for a galaxy to become an AGN is constant in the range of separations sampled in this work and that AGNs can be considered as good tracers of the dark matter distribution as are galaxies.

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